

## 3D Modeling of Fuel Handling System for PFBR Operator Training Simulator

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**Abstract.** Recent advances in computer science have paved way to increased ease in the design of nuclear power plants and imparting efficient operator training thereby improving the safety of nuclear plants. As nuclear power plant is considered safety critical, need to improve the skill set of the control room operators by getting the operator trained in simulator is becoming a mandatory requirement before commissioning the plant. Theoretical models, response and actions in control room panels/consols, human reasoning etc. are simply not enough to impart full understanding of complex systems in reactor to the operators. Over the last few years, addition of 3D models along with the simulated control systems has gained wide attention in training simulators. Additionally, 3D models aid the operator in understanding the system and helps in quicker and more efficient training. One of the most important systems in Prototype Fast Breeder Reactor (PFBR) is its fuel handling system. It requires complex predefined sequential blind operations to be performed by the operator. Many of the operations are needed to be carried out in handling control room through panels and consols. The skill set of the operator needs to be enhanced as the operations are critical and some of them are directly linked with the safety of the nuclear reactor. This paper covers the details of PFBR Full Scope Replica Simulator, various 3D models developed for Fuel handling System along with their associated process and logic models. The sequential procedure based on interlocks and the responses of the 3D fuel handling component models to the operator actions in simulator are also elaborated.

**Key Words:** Prototype Fast Breeder reactor (PFBR), Full Scope Operator Training Replica Simulator, KALBRSIM, Fuel Handling System.

### 1. Introduction

Prototype Fast Breeder Reactor (PFBR) is a sodium cooled, pool type, plutonium-uranium oxide fuelled, reactor with a thermal power of 1250 MWt and an electrical power output of 500 MWe. To ensure safety, design with adequate safety margin, early detection of abnormal events to prevent accidents and mitigation of consequences of accidents, if any, is adopted [1]. Operator training is a prerequisite by Atomic Energy Regulatory Board(AERB) before running PFBR power plant. Full Scope Operator Training Replica Simulator - KALBRSIM used for PFBR is first of its kind in India. KALBRSIM is built with insight based on increased demands on safety and reliability. The KALBR-SIM follows ANSI standard ANS-3.5-1998 for operator training and examination.

Development using 3D graphical software has made rapid progress with an impressive impact in operator training. Now-a-days 3D models are life like, real time and have captured the imaginations of mankind by storm. Usage of 3D graphics in aggregation with KALBRSIM fuel handling system models was quite challenging, more so because of the need to keep the operators' perspective intact. This paper is organized as follows; the first section discusses the architecture of KALBRSIM. The next section deals with a brief discussion on overview of fuel handling systems of PFBR followed by a section on modeling stages of fuel handling system and the steps adopted for modeling 3D. The subsequent section is on the operator

actions /interactions followed by the advantages of using 3D models. The paper is then concluded with a conclusion section.

## 2. Architecture of Full Scope Replica Simulator – KALBRSIM

KALBRSIM is configured around a simulation server class computer, input/output systems, instructor station, operator information consoles /panels, display stations, and a simulation network with power supplies [2]. The PFBR plant role is taken up by the simulator computer. All the mathematical models of PFBR subsystems reside in the simulator computer and they are executed in real time. The simulator computer takes inputs from control panel/console through I/O systems. The inputs are processed by the simulator server class computer and output generated are send to the I/O system for display using indicator/meters, recorders and alarm system in real time. The hardware architecture is shown as below (see FIG.1.).

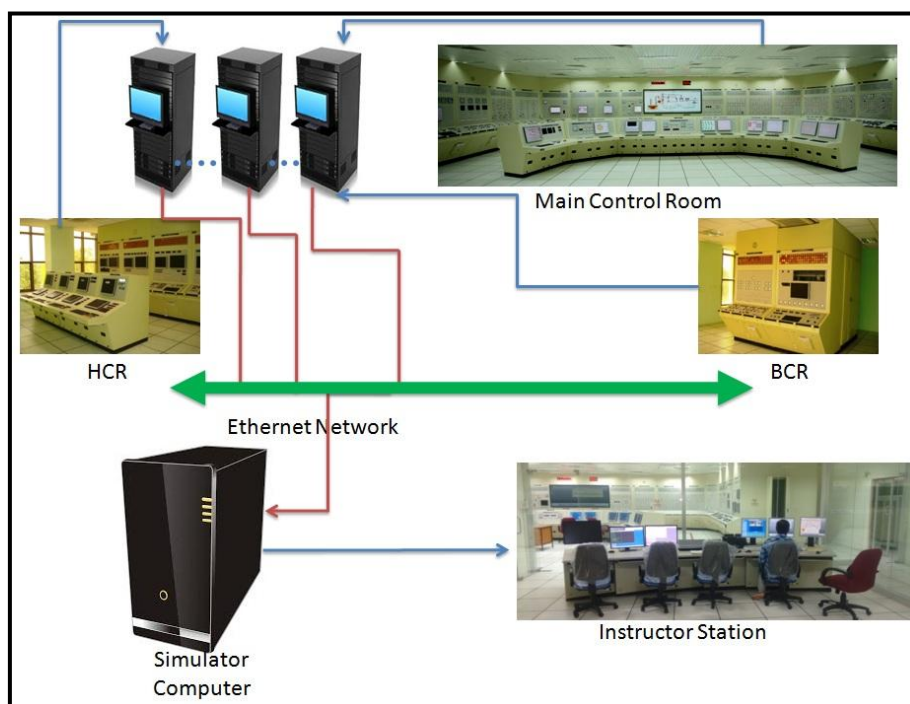


FIG. 1. Hardware Architecture

## 3. Overview of Fuel Handling System(FHS) of PFBR

In PFBR, offline fuel handling is done. Fuel handling system is operational only after the reactor is shutdown. During reactor shutdown, the control rods are dropped to their bottom position and the reactor core temperature reaches around 200 deg centigrade. PFBR has a vertical core arrangement consisting of two rotatable plugs mounted on a roof slab. They are named large rotatable plug and small rotatable plug. In the small rotatable plug, there is a fixed offset machine known as transfer arm which can rotate and can be used for lifting or depositing subassemblies. The combined rotation of both or either rotatable plugs along with rotation of transfer arm covers the entire core area containing the sub assemblies. There are two types of fuel handling systems in PFBR, in-vessel core fuel handling and ex-core fuel handling system. In-vessel core handling involves rotation of rotatable plugs to position the transfer arm above the fuel subassemblies located in the core. Ex-vessel handling is done using cell transfer machine, fresh sub assembly transfer gripper, spent subassembly transfer gripper etc.

## **4. Design and Development of Fuel Handling System**

Simulator software in KALBRSIM contains inbuilt modules for developing process, logic and virtual panels. In KALBRSIM, process models were developed as external models, attached and integrated with logic and virtual panels in UNIX environment. 3D models were developed as independent external models in WINDOWS environment which communicate with KALBRSIM using sockets. Virtual panels are soft panels which were used for testing the process, logic and 3D models of FHS before they were migrated and ported into hardware panels in simulator Handling Control Room (HCR).

### **4.1.Process Models**

The FHS process models in KALBRSIM replicate the plant behavior. In KALBRSIM, FHS process modeling involves discrete event simulation where various interlocks of the system are considered as events. FHS system responds to interlocks and changes its output [3]. Apart from FHS models, reactor startup and fuel handling startup conditions have also been modeled. There are around sixteen mandatory fuel handling startup conditions which need to be satisfied for fuel handling to take place. FHS system operations take place after the reactor is shutdown with all the FHS startup conditions authorized. FHS process models that have been simulated are Transfer Arm and Rotatable Plugs, Inclined Fuel Transfer Machine, Cell Transfer Machine, Under Water Trolley and Spent Subassembly Transfer Machine .

### **4.2.Logic and Control Models**

Logics and controls has been modeled using logic components emulated in software such as AND gate, OR gate, flip-flops, invert, latches, functional blocks etc. The logic model contains the controls and interlocks necessary for initiating operator actions on fuel handling systems. The sequence of operations of fuel handling system involves checking permissives, issuing the command, checking the safety interlocks, checking the various parameters displayed on display panel instruments as well as soft panels and checking the feedback to ensure the operation completion.

### **4.3.Virtual Panel Models**

Virtual panels mimic hardware control and console panel and provide an excellent testing facility [4]. A graphical representation of digital and analog controls in 2D screen is known as virtual control panel. Indicators, Digital Recorders, Lamps, Control Switches, Annunciation Windows etc are replaced with their respective emulated graphical components in virtual panels (see FIG.2.). They can be operated using keyboard and mouse. Virtual panels consist of the same layout as that of the actual plant. Developers make use of the virtual panels to view all simulated signals at a single place. The system developers can do a thorough testing of the system before porting into the actual hardware panel using virtual panel.

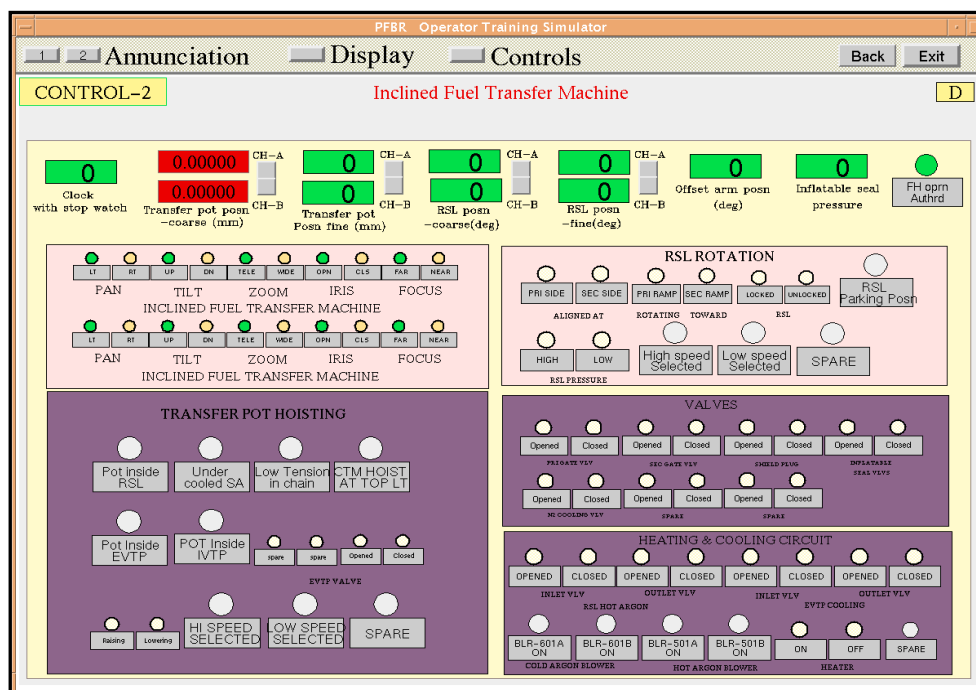


FIG. 2. Virtual Panel

## 5. Development of 3D Software Models

Development of 3D software models was initiated with technical discussions with designers and data collection. Various design documents related to fuel handling systems like control and operation notes, design drawings, P&I drawings and GA drawings etc were collected and studied. Development of 3D models of FHS consist of creating design drawings of various mechanical components using Computer Aided Three-Dimensional Interactive Application tool. General assembly of FHS was completed using the 3D part models. The 3D simulation application outline includes C++ headers and 3D part models. The 3D part models of the various components were imported into the OpenGL based software to assemble them and create a scene graph, such that, various rigid body motions such as rotation and translation can be simulated using functions developed in C++ and be attached to each component in the scene graph. A WinSock function was incorporated in the 3D simulation application on windows platform. A UDP socket was created and binded with port address of simulator server which executes in UNIX platform. Send and receive functions were incorporated in both the applications and successful communication was established and tested. The C++ code developed was then integrated with the associated control logic models of the various FHS components implemented on the simulator server. Integration of developed logic models with the FORTRAN based Neutronics model was also carried out on the simulator server. The animated 3D models with the display GUI screens were modeled (see FIG.3.) in HCR.

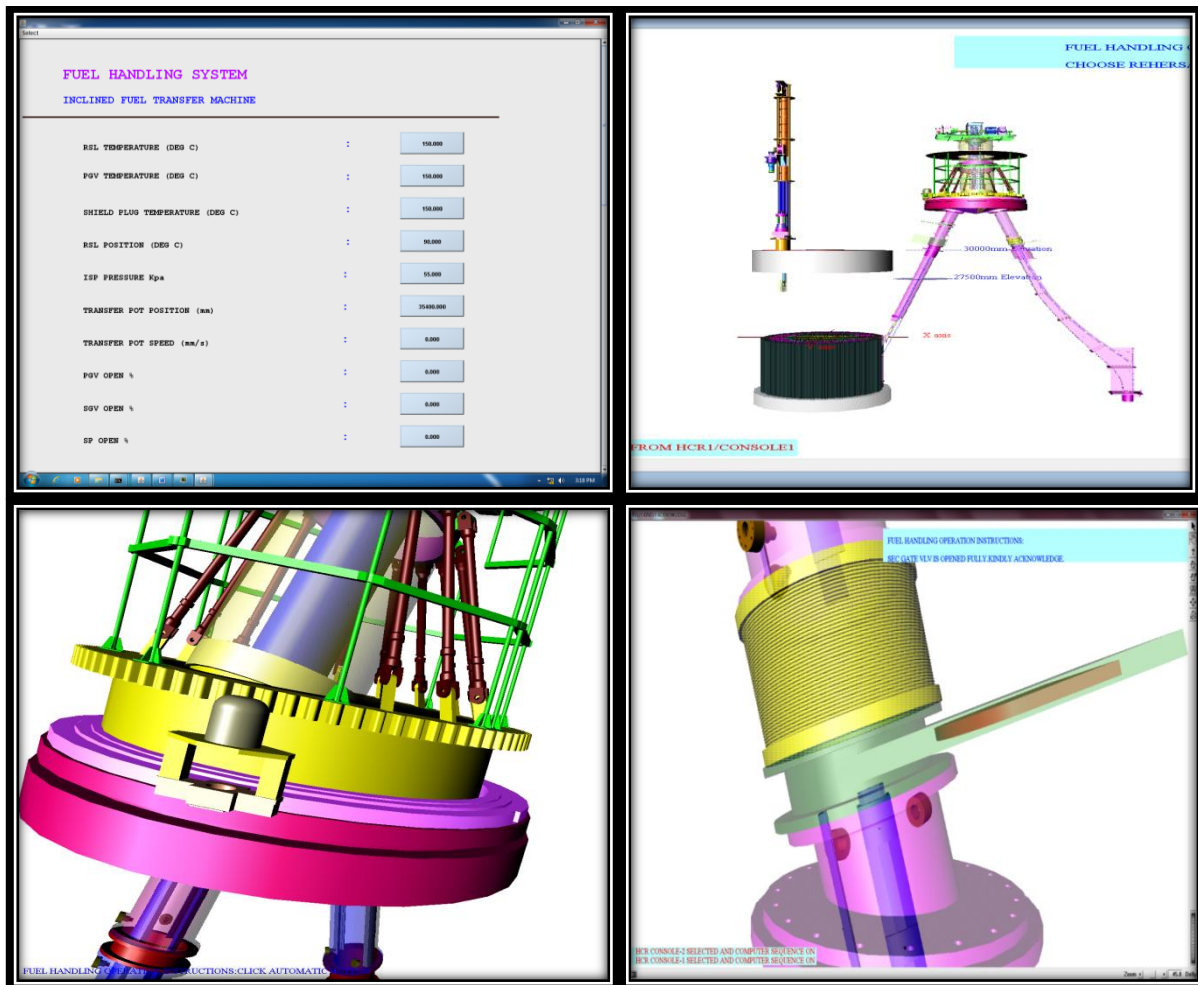


FIG. 3. 3D models with GUI screen

### 5.1.Scene Graph Modeling

The scene database consists of a group of scene graphs. Each scene graphs are composed of 3D objects such as Transfer Arm, Inclined Fuel Transfer Machine, Cell Transfer Machine, Under Water Trolley etc. The scene graph was written using C++/OpenGL programming. Scene graph consist of root node with children nodes (see FIG.4). The root node also contains camera with light. The root node is nothing but the main/top node which represents a group of other nodes (children nodes). Note that all children nodes are not listed in the below figure. Some of the children nodes themselves are group nodes. Each child node is associated with a geometry and property.

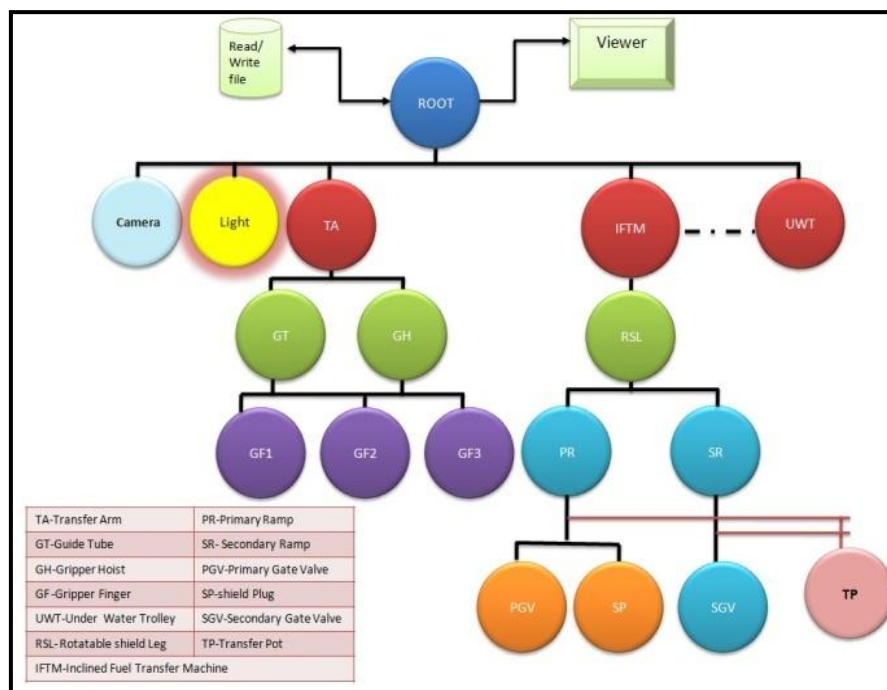


FIG. 4. Scene Graph

The placement of components in the scene graph is such that they are placed with respect to the reactor core with the distance as per the actual component placement in the plant. The scale is matched as per the design drawing. The centre of the viewing window will be placed at (0,0,0) Cartesian co-ordinates. The application scene graph consists of headers and imported 3D models. A simple perspective camera was placed for viewing. The camera node was placed near the top left as it has to precede all other nodes in the scene graph. The C++ code was written such that the camera node position, near distance and far distance fields with aspect ratio and height was set to view the entire scene graph at the beginning of the execution. Only one active camera was modeled in the FHS application. Objects outside the camera were clipped off. The light node uses the Phong lighting model. The light sources are combined with material properties to give the shading.

## 5.2. Modeling of Kinematics

The kinematic modeling consist of transformations such as translation and rotation . These actions are required for the components to perform the operation based on control inputs and interlocks. Hence components which need to perform dynamic actions and which need to be animated are identified and transformation function threads were attached to it. The components that need to be animated are Guide Tube Raise/Lower, Cell Transfer Machine movements, Gripper Hoist Raise/Lower, Gripper Fingers Open/Close, Long Carriage Travel, Vessel Plug Open/Close etc. The camera position, near and far distance was changed depending on the operator interaction with the scene graph. The viewer tool was also provided with zoom, pan and other facilities. The transformation function threads incorporate a user defined callback which gets invoked when any event gets triggered. These function threads are attached to the scene graph database. Priority is set to each thread and a field is attached with the thread. Whenever there is an user action, the function gets triggered and gets scheduled, as in the case of transfer pot, translation movement in the primary ramp gets triggered, when the operator presses lower/raise button from HCR panel. On completion of translation movement, the function gets unscheduled. The application is built with a user interface inside which the scene graph is drawn. A viewer is created and configured to display

and an event loop is triggered to get the transformation function response. After the response due to user action is completed, the transformation function thread gets unscheduled.

### 5.3. FHS 3D Model Connectivity with External FHS Model in Simulator

KALBRSIM external model for FHS was developed using C language in simulator. The model was organized to include initialization with run time block and IPC handler functions. The IPC handler was organized as follows,

- **Published Variable Function**

This function is used for registering variables for publishing into the simulator environment. The published variable is send to simulator environment for further processing/display etc. For example, some of the outputs generated by the FHS external code triggers alarm, in that case this alarm output will be send to another external code which is exclusively used for Alarm Generation in simulator via Message and Data Sharing Mechanism (MDSM).

- **Subscribed Variable Function**

These variables are needed by the FHS model as inputs from the simulator environment for further processing. Inputs are generated either by user actions, such as operator pressing a lower/raise push button from hardware control panel. This operator action is subscribed as input inside the FHS external code to generate an output.

- **Process Functions**

These are the mathematical functions which need to run every cycle in simulator. The model calculations and logics associated with FHS are done in process functions. For example, if the operator selects core location positioning switch from hardware panel, the transfer arm controller function checks the current position of the transfer arm. The transfer arm is permitted for rotation only if the offset arm is between 0 degree to -ve 90 degree position. If the offset arm lies between 0 degree and +ve 90 degree, there will be an error message and the rotation of TA will not be permitted because of an interlock. This interlock is provided to avoid entanglement of offset arm with another machine called the Inclined Fuel Transfer Machine.

FHS external model in Unix Environment residing in simulator server connects to FHS 3D animation system through User Datagram Protocol(UDP) socket (see FIG.5). In the simulator server, the 3D FHS signals are received using non blocking UDP receive function. The received data is then distributed among other internal simulator models through shared memory based publish/subscribe communication mechanism. The simulated data is sent to hardware panels and display stations. Similarly, the hardware panel inputs are received by an external code written for panel input/outputs. This command data is published by that external code to MDSM which in turn is subscribed by the FHS external code. The 3D animation is a multi threaded application. The UDP communication with simulator server is handled by one thread. The other tasks such as scene rendering and computation of FHS parameters and animation of 3D models are carried out by the other threads including the transformation function threads. All these threads are synchronized using global variables. After 3D simulation is successfully integrated with external FHS models executing on simulator server, normal operation or malfunction initiation from instructor station is executed and the response and behavior of 3D animation application is verified and validated.



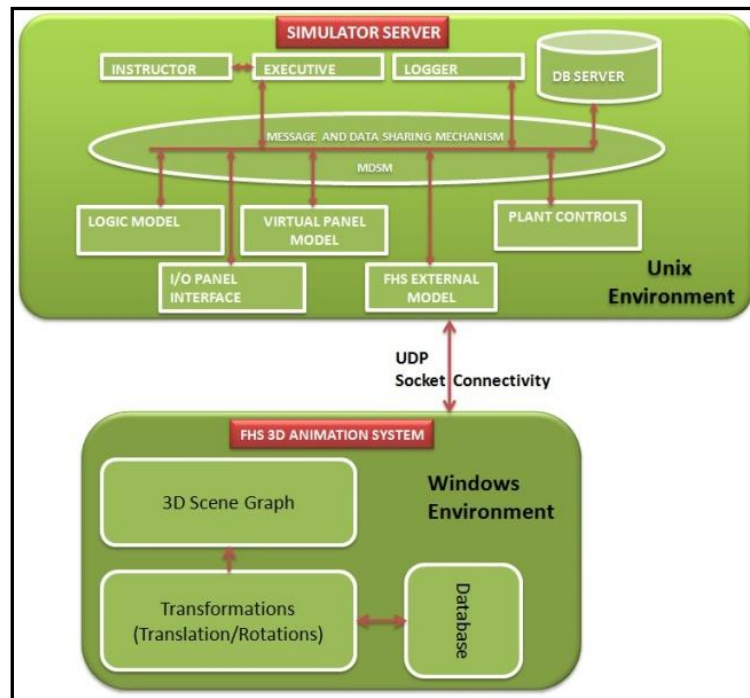


FIG. 5. FHS Architecture

## 6. Operator Actions

Each of FHS operation involves sequence of steps, with acknowledgement issued by the operator at each and every step. The operator actions can be done either manually or through computer guided mode. If the operations are carried out manually then it has to be done in Handling Control Room using panels or consoles which contain hardware buttons and switches. If it is computer guided, then it is done with the help of display station. The operator chooses the drive which is planned to be operated from the hardware, followed by the mode selector switch. By using the keyboard or mouse of the display station, the desired operation is then carried out. The control systems ensure that the operations are executed if and only if, the interlocks and the permissive/necessary conditions are satisfied. The sequence of FHS operations are all in a series of steps i.e., the operation are carried out in a sequential manner only. Each step involves checking the permissive, issuing the command if permissives are satisfied, checking the safety interlocks of the component being commanded to operate by the operator and checking the feedbacks for ensuring the operation completion. After each step of operation completion, the operator has to acknowledge his action. Only after acknowledgment, the operator can select the next step in the sequence. The computer guided sequence of operations are done using soft GUI (see FIG.6.). This GUI will be displayed in display stations at Control/Console in Handling Control Room. Even though all the operations are carried out using display station GUI, the drive selection, mode selection, function selection etc are carried out only through hardware switches provided in the HCR.



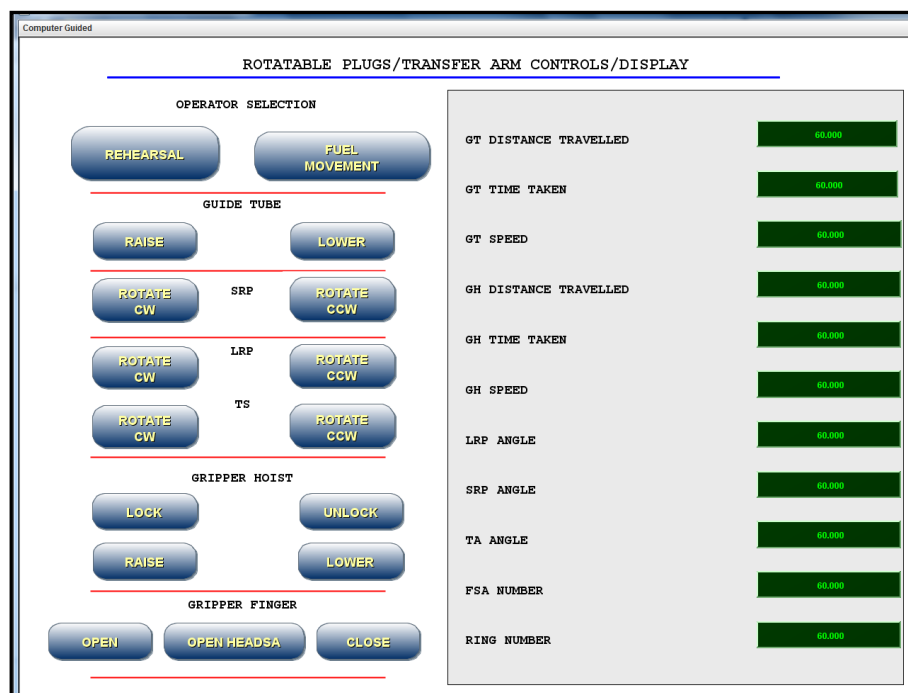


FIG. 6. Computer Guided Sequence for TA/RP operations

## 7. Advantage of Using 3D Models in FH System

Some of the advantages of using 3D models in FH system are listed below,

### 7.1. Superior Teaching Tool

Conventional methods of teaching plant operators with simulator using only hardware panels/conssoles with soft panel GUI is found inadequate for imparting full knowledge on system as many of the operations carried out by the operator are blind and has to be done based on imagination only. The operators are guided by hardware/software LED signals, recorder signals, soft alarms etc only. But with the aid of 3D models, while performing the operations, the operator can visualize the system accurately.

### 7.2. Captures Attention

The 3D models being drawn inline with the actual PFBR components, the operator is able to visualize the placement of the components in PFBR Fuel handling building and their relative size with each other, this being very useful whenever the operator has to do field operation in the actual fuel handling building. For example, if the operator has to do a valve close operation, the actual placement of the valve with respect to the component is easily understood and hence when the operator has to do the field operation the knowledge is highly valuable.

### 7.3. Improves the Operator Reflexes

The malfunction/transients loaded in the simulator are quickly analyzed by the operator on seeing the 3D model behavior. When the animation stops due to any malfunction/transient loaded by the instructor, the operator is able to start diagnosing the behavior quickly. Thus greatly improving his reflexes.

## 8. Conclusion

Training with simulator is a mandatory requirement from AERB before commissioning any nuclear plant. Hence training an operator has to be done in such a way that the operator actions are perfected before they start operating the actual systems.

3D models are very beneficial during operator training period as they are able to better visualize fuel handling systems operation in the plant. Some of the advantages of using 3D models are listed in section 7. The feedback obtained from the operators after undergoing training using 3D models in simulator are very encouraging. It is planned to take other subsystems of PFBR for 3D modeling where the system operations are complex to understand by the operators.

## Appendix 1:

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